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Regional Scale Mapping of Debris-Flow Susceptibility in the Southern French Alps

Mélanie Bertrand, Frédéric Liébault and Hervé Piégay

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Introduction

1 The issue of natural hazards in mountainous areas has led to numerous studies seeking a better understanding of and a better ability to predict the conditions of occurrence, intensity and effects of natural phenomena that present inherent risks. The integration of research development in this area – in particular, the approaches addressing hazard assessment at a regional scale – within risk analysis is crucial to improve their management in both the long term (sustainable land management, preventive management) and the very short term (crisis management).

2 Debris flow is recognised to be one of the most destructive hazards in mountainous areas (Jakob and Hungr, 2005), generates a lot of damage and sometimes causes casualties, like during the Biescas disaster in the Spanish Pyrenees in August 1996 (Lajournade *et al.*, 1998). Debris flow can be defined as a rapid mass movement of a mixture of water, organic matter and sediment of varying size that generally occurs as bursts with a sediment concentration greater than 50% (Coussot and Meunier, 1997; Chambon and Laigle, 2013; Liébault *et al.*, 2013). Depending on the grain-size distribution of the solid phase (Bonnet-Staub, 1998, Remaître *et al.*, 2005), it can be classified as granular or cohesive. Significant efforts have been made over the past several years to predict the spreading of debris flows at the local scale on the alluvial fans from physically based models (Laigle *et al.*, 2006; Toyos *et al.*, 2007). However, these local approaches cannot be

transposed to regional scales, and the development of methods adapted to characterising torrential phenomena over large spatial area is still limited (Horton *et al.*, 2008; Miller and Burnett, 2008; Kappes *et al.*, 2011). These macro-scale approaches should cover both (i) the analysis of predisposing conditions to debris-flow activity (susceptibility analysis taking into account both sediment availability in the catchment and in the channel and the slope and morphometric characteristics of the catchment) and (ii) hydrometeorological conditions allowing the triggering of debris flows (Wieczorek and Glade, 2005). Thus, a regionalised knowledge of debris-flow susceptibility is essential to identify the sites sensitive to high-intensity rainfall events and to plan regional strategies of risk management.

3 Thanks to the RTM services (National Forest Office services in charge of torrent-control works in France), catchments prone to debris flows in highly vulnerable areas in the French Alps are well known. The RTM database (http://rtm-onf.ifn.fr/), which is available for all French Alpine massifs, has recorded nearly 30,000 events (including all types of events) over the past few centuries in the Southern Alps and is regularly updated by the RTM services. It lists the impacts of torrential activity without systematically distinguishing the nature of the processes involved (flood or debris flow). The identification of processes and the prediction of their intensity at a regional scale are therefore not conceivable solely on the basis of this partial knowledge of the hazard. The production of datasets at a regional scale and the development of methodologies to produce them are therefore still important research issues.

4 In this context, the aim was to develop a methodology to report debris-flow susceptibility spatially at a regional scale (i.e. the evaluation of its potential spatial occurrence, not the physical study of the debris-flow phenomenon) and to apply it to the Southern Alps. Geomatic and statistical methods have been implemented. This methodological choice is explained by the fact that, at a large scale, it is impossible to constrain all the input variables required to apply physically based approaches at local scales. The result is a map that characterises the susceptibility of small mountain catchment to debris-flow phenomena, which does not qualify either the volume or the 2D propagation of the flows.

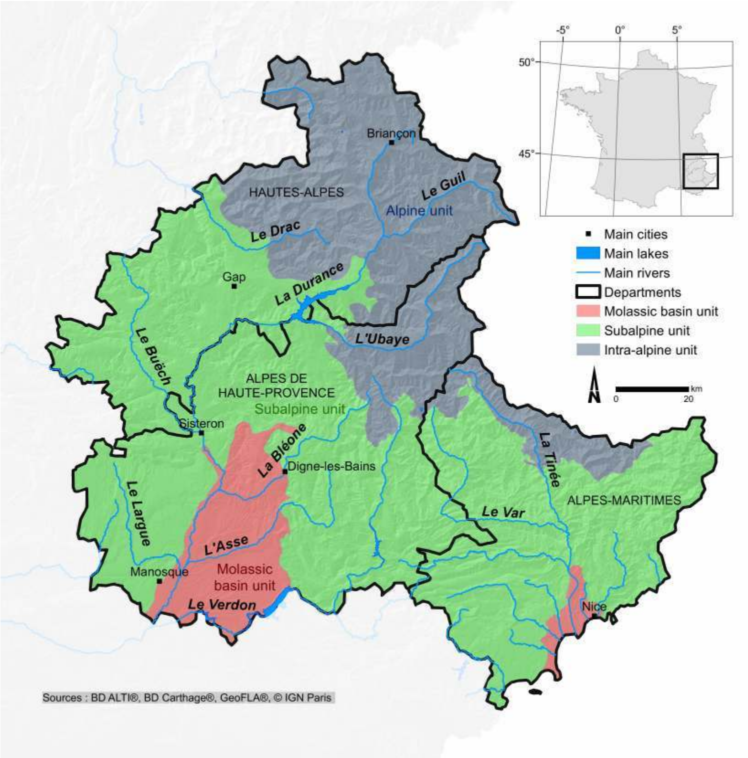
5 The methodological developments presented in this paper aim to distinguish the dominant types of flow (debris flow and bedload transport) within the hydrographic network.

6 This approach is based on the integration of various factors of predisposition to debris flows (Bonnet-Staub, 1998), in particular (i) the morphometric characteristics of the reaches and their catchments and (ii) their potential sediment supply. For each of these factors, the methodological developments have been specific and are detailed in the methodology section.

Study area

7 The study area (Figure 1) extends between 43°28'N and 45°08'N and 5° 30'E and 7°42'E. It covers almost the entirety of the Southern French Alps and includes part of the Mediterranean coastline. The mapping work fully covers the three alpine departments of the Provence-Alpes-Côte d'Azur region, namely Hautes-Alpes (05), Alpes-de-Haute-Provence (04) and Alpes-Maritimes (06), which together comprise a spatial area of ~16,900 km².

Figure 1. Study area and its main geological units



8 This territory covers three major geological units: (1) the intra-alpine zone, (2) the subalpine zone and (3) the molassic piedmont. The highest massifs (up to about 4,100 m in the Écrins massif) are found in the intra-alpine zone, along with the outcropping of the basement of the crystalline massifs (Paleozoic), metamorphic rocks and extensive areas of sedimentary rocks. This zone was greatly affected by the presence of glaciers (still present in the Écrins) during the last glacial maximum (LGM).

9 The subalpine unit is less elevated since the maximum altitudes are below 2,000 m, except locally in the Dévoluy massif and in the upper valley of the Bléone River. The highest areas (Haute Bléone, Haut Verdon and Drac) were also glaciated during the LGM; however, glacial imprints (moraine deposits) are less developed than in the intra-alpine zone. This unit is made up exclusively of sedimentary rocks, mainly alternations of limestones and marls. In this unit are the Terres Noires, namely Jurassic black marls very sensitive to erosion. This type of rock covers a significant portion of the subalpine domain, especially in the Durance River basin (~100,000 ha) (Mathys *et al.*, 1996).

10 The third and lowest (less than 1,000 m) unit corresponds to the molassic domain and consists of tertiary sedimentary rocks (mainly conglomerates and sandstones) in the Alpes-Maritimes department.

11 The length of the hydrographic network for which we characterised debris-flow susceptibility is about 19,000 km, which corresponds to the network for which the drainage area is less than 40 km². This size criterion corresponds to the largest catchment known to produce debris flows in the French Alps (the Boscodon, near the Serre-Ponçon reservoir).

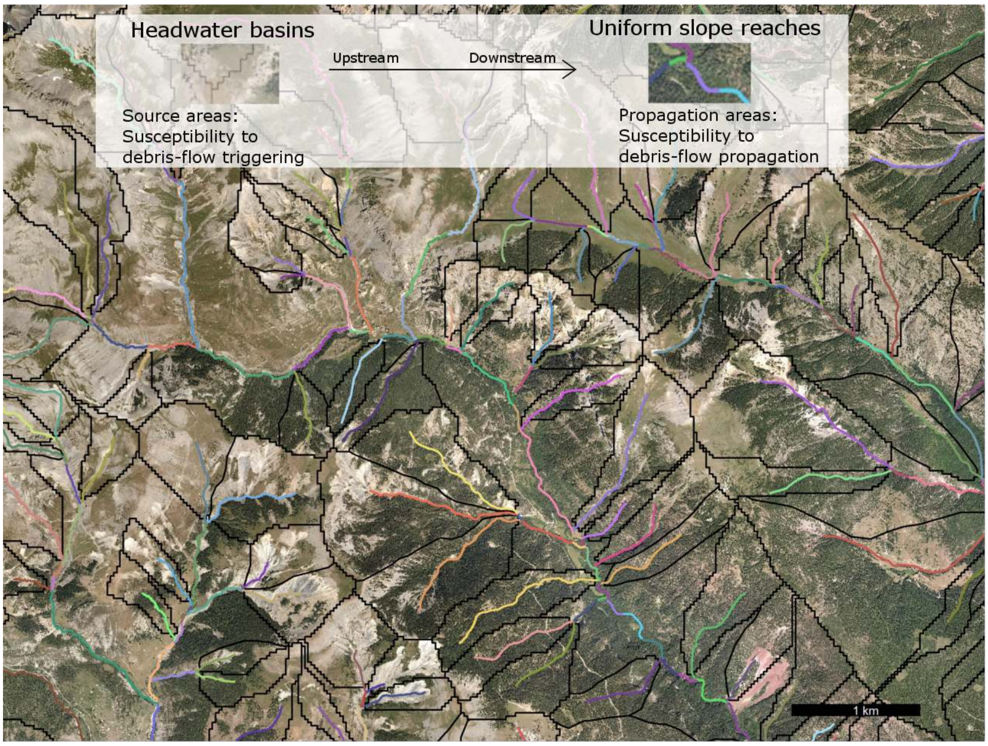
Debris-flow susceptibility map: methodological approach

12 Based on spatial units defined below, the debris-flow susceptibility map integrates two predisposing factors: (1) the morphometric properties of the torrents and their catchments that make it possible to evaluate the available gravitational energy to trigger and propagate debris flows and (2) the sediment supply of the catchment controlling debris-flow triggering. These two criteria help to evaluate the morpho-sedimentary probability of debris-flow occurring.

Identification of the spatial units

13 This analysis is based on two elementary spatial units: (1) the headwater catchment that provides debris and (2) elementary reaches with uniform slope transferring the sediment downstream (Figure 2). The headwater catchments (corresponding to reaches of Strahler's stream order 1 and 2) are considered as source zones for which the capacity to supply materials and the energy available for triggering debris flows are evaluated. They were delineated from a hydrological analysis carried out on a 25-metre DEM (BD TOPO®) under ArcGIS™ (extension ArcHydro© Tools). The lower limit of the drainage area of the headwater catchments corresponds to the smallest low-order channels represented in the BD TOPO® hydrographic network.

Figure 2. Definition of the spatial units



14 The torrential hydrographic network is also cut into sections of reaches with uniform slopes to evaluate, section by section, the energy available for the propagation of debris

flows. They were defined after the reaggregation of 50-metrelong unit segments based on the statistical detection of breaks in the longitudinal series of slopes.

15 This identification of functional units is based on a simplification of the complex debris-flow sediment cascade, which cannot be solved at a regional scale. Numerous case studies have shown that the torrential channels located downstream from the production zone are often important sediment sources related to debris-flow scouring (Remaître *et al.*, 2002, Theule *et al.*, 2012). Consideration of these channel processes at a regional scale implies the development of tools for the automatic recognition of loose sediment stores in steep-slope channels, which are not yet available.

Statistical model of discrimination of torrential responses

16 A statistical model has been defined to discriminate torrential responses according to the type of dominant flow observed at the outlet (debris flow or bedload transport). The Melton index (equation 1) and the slope of the alluvial fan are frequently used to identify torrents that are prone to debris flow (e.g. Jackson et al., 1987; Kostaschuk et al., 1986; Marchi et al., 1993; Marchi and Brochot, 2000). The fact that these works reach similar conclusions in distinct geographical areas (European Alps, Canada's British Columbia, New Zealand and the Pyrenees) confirms that these morphometric indicators are fairly robust and adapted to the prediction of torrential responses.

Equation 1. Melton's index

$$R = \frac{Z_{max} - Z_{min}}{A^{0.5}}$$

In this equation, *R* is the Melton index, *Zmax* and *Zmin* the catchment maximum elevation and the catchment outlet elevation, respectively, and *A* the drainage area in km².

17 On the basis of these studies and the published data of 620 catchments, a logistic regression model was designed. This model provides a probability distribution of debris-flow activity as a function of the slope of the reach and the Melton index of its upstream catchment. Sensitivity and specificity indicators, representing the ability to predict positive (debris flow) and negative (bedload transport) cases, respectively, were calculated to evaluate the performance of this model (Begueria, 2006). Considering a cut-off probability of 0.5, sensitivity and specificity scores of 0.95 and 0.75, respectively, were obtained. The entire statistical approach is described in full in Bertrand *et al.* (2013).

Automatic mapping of erosion

18 Active erosion patches represent areas likely to supply sediment to the hydrographic network; thus, it is a major predisposing factor for triggering debris flow (Bonnet-Staub, 1998; Cenderelli and Kite, 1998). At regional scales, however, an assessment of available sediment volumes with the field methods usually applied to small catchments is not feasible. Remote sensing methods using infrared orthophotos (831 tiles, 0.5m resolution) and Landsat 7 ETM+ images (three images, with 30 m resolution and offering a wider spectral range than orthophotos) have been developed. This type of data is particularly suitable to a detailed mapping of land use, particularly of the erosion zones (Metternicht

and Fermont, 1998; Begueria, 2006; Vrieling *et al.*, 2007; Torkashvand, 2010). But the development of a method to map erosion areas from such data sources remains a methodological challenge at this scale.

19 We randomly selected 30 tiles of infrared orthophotos to constitute a training dataset of the erosion classification model. These tiles were automatically segmented into objects of homogeneous texture and classified manually into two categories (erosion/no erosion). The approach is based on a fusion (weighted sum) of several supervised classifications of infrared orthophotos and Landsat 7 ETM+. Thirty other tiles were randomly selected to create a validation dataset. They were segmented and classified manually by means of photo interpretation and then compared with the different classification methods and the final model in terms of sensitivity and specificity. Details of this analysis are available in Bertrand (2014).

Integration of predisposing factors

20 The two predisposing factors are first assessed from simple indicators to evaluate the morphometric potential and the sedimentary potential of the catchments and then combined to form classes of morpho-sedimentary susceptibility. The morphometric probability of debris-flow activity is discretised into four classes (null $P \leq 0.02$, low $0.02 \leq P \leq 0.5$, intermediate $0.5 \leq P \leq 0.75$, and high $0.75 \leq P \leq 1$). To assess the sediment potential, erosion surfaces are cumulated in the triggering zones (small headwater catchments) and normalised by the drainage area. If this active erosion area represents more than 50% of the catchment or if there are erosion zones of more than 5 hectares in the catchment, the potential is classified as high, or vice versa as low.

21 In small headwater catchments, classes of debris-flow susceptibility are defined by combining classes of morphometric probability of occurrence and sediment availability classes, according to a rule-based approach based on expert field observations, as summarised in the following matrix (Table 1).

Table 1. Classification rules of the susceptibility to debris-flow triggering, integrating the morphometric potential and the sediment availability

		Debris-flow susceptibility of low-order reaches according to the morphometric potential			
		Null P≤0.02	Low 0.02≤P≤0.5	Intermediate 0.5≤P≤0.75	High 0.75≤P≤1
Debris-flow susceptibility of low-order catchments, according to the sedimentary potential	Low	Null	Low	Low	Intermediate
	High	Null	Intermediate	High	High

22 Further downstream on the hydrographic network, classes of debris-flow susceptibility are defined for reaches of uniform slope according to decision rules based on expert field observations, as summarised in the following matrix (Table 2). For a given section of

reach, debris-flow susceptibility class is the result of the adjustment of the class of morphometric probability of occurrence of debris flow according to the susceptibility conditions of the section of reaches located just upstream. This adjustment is reflected recursively from upstream to downstream.

Table 2. Classification rules of the susceptibility to debris-flow propagation, integrating the morphometric potential and the sediment availability within the longitudinal dimension

		Debris-flow susceptibility of the current section of reach according to the morphometric potential			
		Null $P \leq 0.02$	Low $0.02 \leq P \leq 0.5$	Intermediate $0.5 \leq P \leq 0.75$	High $0.75 \leq P \leq 1$
Highest debris-flow susceptibility class of the upstream HSR, according to the morphometric and sediment potentials (adjusted class)	Null	Null	Null	Null	Null
	Low	Null	Null	Low	Low
	Intermediate	Null	Low	Intermediate	Intermediate
	High	Null	Low	Intermediate	High

Susceptibility to debris flows in the Southern Alps

Application of the statistical model

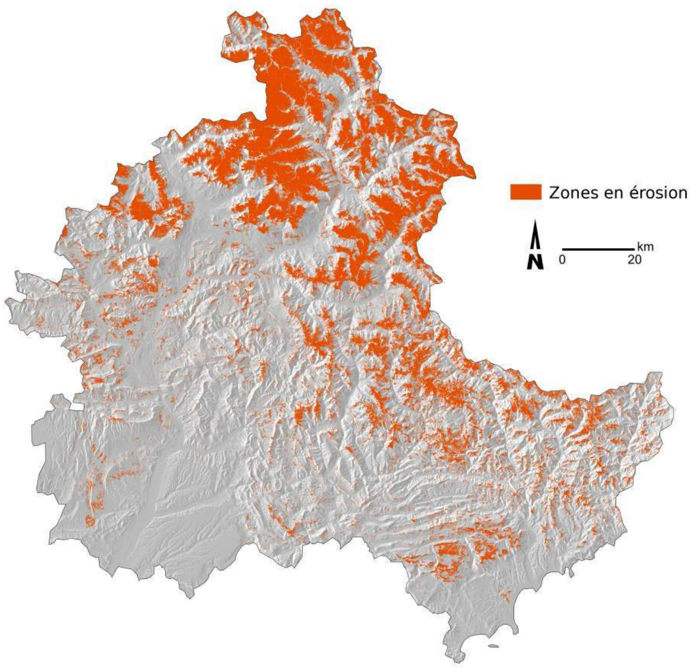
23 The extraction of the morphometric indicators was carried out under ArcGIS ™ from the digitised hydrographic network (first topologically corrected by hand) and the 25-metre DEM from IGN (BD TOPO ©). For each elementary reach, we calculated the slope (in degrees) of its downstream part (potentially corresponding to a deposition zone), the difference between the maximum altitude of its catchment and the altitude of its outlet (in m) and its drainage area (in km^2). These variables were used to calculate the Melton index and the slope of the reach at the outlet, both of which are needed to predict the morphometric probability of debris flow occurring.

Automatised erosion mapping in triggering zones

24 The remote sensing approach made it possible to establish a classification model for erosion with sensitivity, specificity and overall classification scores of 0.81, 0.94 and 0.90, respectively (Bertrand, 2014). An expert validation was also carried out from 500 points randomly distributed in the Bléone catchment. It records fairly similar scores (0.74, 0.99 and 0.96) (Liébault *et al.*, 2015). This validation does not prejudge the ability of the classification model to spatially delineate the erosion zones but helps to confirm that for a randomly selected pixel the model is capable of determining whether it is included in an erosion zone.

25 These two types of validation indicate that there are some erosion zones that the model does not detect. These zones are preferentially located in black marl outcrops covered with sparse vegetation or in masked areas (shadows due to relief). The map of erosion zones obtained from the methodology described above is presented in Figure 3.

Figure 3. Map of erosion patches established from the analysis of the infrared orthophotos and the Landsat 7 ETM+ images



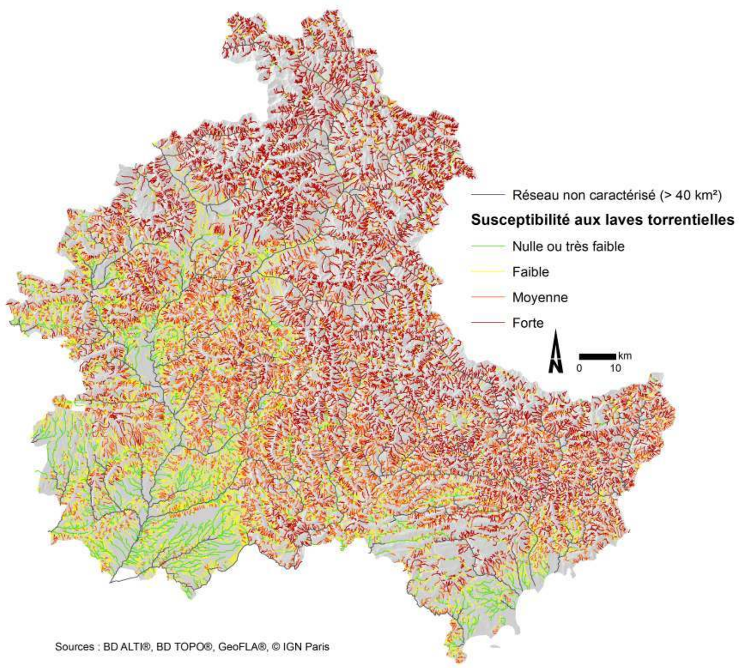
Sources : BD ORTHO IRC® (2009), BD ALTI®, © IGN Paris; Landsat ETM+ (2001-2003)

Bertrand, 2014.

Debris-flow susceptibility integrating the two predisposing factors

26 The two matrices allowed defining the susceptibility class of all sections of reaches of the hydrographic network whose catchment size did not exceed 40 km². The map in Figure 4 shows the susceptibility to debris flows in the triggering zones and in the downstream propagation units.

Figure 4. Map of susceptibility to debris-flow triggering and propagation

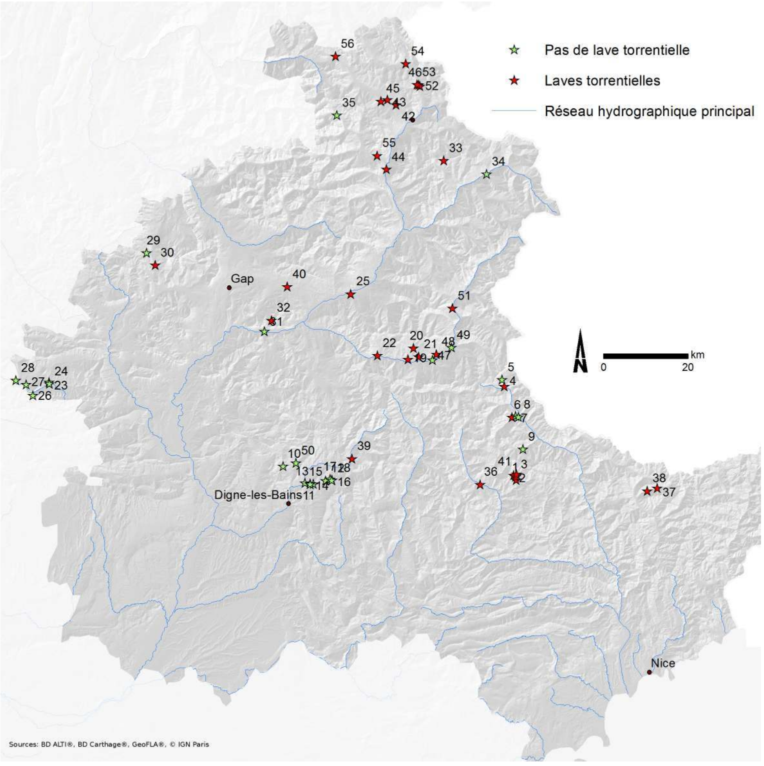


Bertrand, 2014.

Validation of susceptibility to debris flows and presentation of the maps

27 Susceptibility classes were validated using 56 control sites (Figure 5) classified according to the dominant sediment transport process (31 torrents prone to debris flow and 25 torrents with only bedload transport). These observations show that the susceptibility map is reliable and robust. Sensitivity, specificity and overall classification scores of 0.71, 0.92 and 0.80 were obtained, respectively, which confirms the predictive capacity of the approach.

Figure 5. Spatial distribution of the 56 sites used to validate the map of susceptibility to debris flow; these sites are well known from experts, either because they were specifically studied or because they recently produced debris flows that were well documented



28 The susceptibility map presented in this article can be consulted on a Web platform of services deployed as part of the RhyTMME project (http://rhytmme.irstea.fr/). This project is based on the deployment of X-band meteorological radars in the Southern Alps, which Météo-France's Aramis radar network did not cover correctly. These new radars provide real-time monitoring of rainfall intensity (Westrelin *et al.*, 2012). The aim of this project is to establish, in the long term, a warning platform for natural hazards related to precipitation in order to allow local managers to anticipate dangerous events. The RhyTMME platform allows the superposition of the debris-flow susceptibility map with rainfall maps for several durations (from less than an hour to several weeks) in order to identify catchments susceptible to triggering debris flows. The platform also proposes superimposing the debris-flow susceptibility map on a landslide probability map, since the hazard of debris flow may be amplified by landslide activity (Fouchier *et al.*, 2016).

29 During an initial experimentation phase, the RhyTMME platform had 100 users and about 40 public structures or services (local and regional authorities, RTM services, rescue services, river basin management authorities, railway and power plant companies). These actors, closer to their territory, provided us with valuable feedback for the improvement of the susceptibility map.

Discussion and outlook

30 An analysis of the quality of the information delivered on the RhyTMME platform in terms of torrential susceptibility reveals that the hydrographic network is generally well classified. Nevertheless, the feedback gained from the events that have occurred since the

map was put online shows some cases of debris flow that have propagated on sections of reaches classified as between null and a very low susceptibility, like the debris flow that occurred in the Riou Sec in Haute Ubaye in July 2015, which cut off route RD125. Other cases of wrong classification were also observed during the evaluation of the map (see the scores given in the validation section), which showed too optimistic a display of susceptibility (the specificity score is better than that of sensitivity). From a practical point of view, this means that certain sections of reaches classified as null and low susceptibility, or even average, present an underestimation of the hazard regarding the physical reality of the phenomenon.

31 The examination of each misclassified section shows that the problem is very often due the geomatic procedure. Some errors are due to outliers on the 25-metre DEM, which remain even after the pre-processing steps. Others are related to the inconsistency of the superposition of the vectorial hydrographic network on the DEM. The fact that the network is not always located at the lowest point in the talweg (it passes over a terrace or a hillslope) leads to errors in the evaluation of the slopes. This is related to the low resolution of the DEM. This also leads to a poor discretisation of the hydrographic network into homogeneous slope sections. Here, the Hubert statistical algorithm applied on slope values of the 50-metrelong segment led to the formation of very short homogeneous sections with mean slopes lower than they would have recorded if they had aggregated more 50-metrelong unit segments. Since they are located in confluence zones, where the relief is smaller and the bottom of the valley is wider, these short sections underestimated the torrential hazard. Beyond the lack of precision of the DEM used, it is also the sensitivity of this statistical Hubert test that is called into question. Improving the parameters of this test would avoid the few problems of over-segmentation of the hydrographic network.

32 A 5-metre DEM produced by radar interferometry is now available throughout the territory and offers the possibility of relaunching a spatial analysis of the sections of reaches. Its use would lead to a better evaluation of the slopes, making it possible to overcome a number of problems such as those mentioned in the preceding paragraph. For the automatic delimitation of catchments, its use in a restricted zone of the Alpes-Maritimes department confirmed a net improvement of performances compared with the 25-metre DEM (Bertrand 2014).

33 Another improvement on the debris-flow susceptibility assessment method would be to update the map of erosion patches regularly in order to have a dynamic assessment of the state of the surface of these zones, which give an indirect indication of the sediment recharge into steep reaches. This step of mapping, which is already automatised, could be applied to satellite Pléiades images, as they show the same characteristics as the orthophotos (50 cm in resolution, similar spectral resolution in the visible and infrared domains). These images cover a very high temporal resolution, as the coverage is updated daily, and would allow characterising the sediment recharge after high intensity events.

34 The regional assessment of debris-flow susceptibility should also be improved by integrating other feedbacks on the physical reality of torrential phenomena. The validation dataset should be extended with other observation sites, as its size is relatively reduced (56 sites) compared with the length of the hydrographic network we characterised. A systematic analysis of the torrential events that occur after convective rainfalls of high intensity would improve the assessment of the effects of conditions of sediment recharge into headwater catchments. The spatial distribution of these rainfall

events can now be reconstructed from a retro-analysis of the radar data from the RhyTMME project and compared with a field analysis of the recent torrential responses. This kind of study is now feasible and promising not only for the determination of sediment recharge proxies but also for the determination of critical rainfalls for the triggering of phenomena (Marra *et al.*, 2014).

35 From a static map of debris-flow susceptibility to a hazard map, integration of meteorological forcing is needed. Critical rainfall conditions allowing the triggering of debris flow have been identified thanks to an intensity duration threshold based on data obtained from a very active torrent in the Alpes-Maritimes department (the Réal torrent) (Bel *et al.*, 2016). Implementation of this threshold on real-time data (from meteorological radar of the RhyTMME project) and its integration with the static susceptibility map would permit making predictions of torrential hazards more dynamic.

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ABSTRACTS

This article describes a regional methodology of debris-flow susceptibility mapping. The implementation of this approach is based on statistical and GIS methods and makes it possible to identify catchments in the Southern French Alps, according to their morphometric (Melton index and local slope) and sediment supply conditions (active erosion zones in headwater catchments), that are prone to debris flows because of hydrometeorological forcing. This methodology has been validated on 50 sites with very high scores; the geomorphic response was correctly predicted for 80% of the sites. The map of susceptibility to the occurrence of debris flow has been integrated into the RhyTMME project’s Web platform. This platform also offers a visualisation of the rainfall’s spatial distribution (from meteorological radar data), enabling automatic real-time detection of the triggering of debris flow at the regional scale.

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Keywords: susceptibility, debris-flow, Southern French Alps, GIS, remote sensing

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